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Cardiac Catheterization of Patients Supported by Extracorporeal Membrane Oxygenation

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OBJECTIVES The goal of this study was to describe the clinical outcomes of patients undergoing cardiac catheterization while supported with extracorporeal membrane oxygenation (ECMO).

BACKGROUND Extracorporeal membrane oxygenation is an important mechanical support for the failing circulation. There are diagnostic and therapeutic indications for cardiac catheterization in patients on ECMO, but no large series has been reported.

METHODS We performed a retrospective review of the indications and outcomes of patients catheterized on ECMO from a single, large pediatric tertiary care center.

RESULTS At our institution, 192 patients with cardiac disease have undergone a total of 216 courses of ECMO; 60 catheterizations were performed on 54 patients (28%). Indications for catheterization included assessment of surgical repair (21 patients), left heart decompression (12 patients), myocarditis/cardiomyopathy assessment (10 patients), non-post-operative hemodynamic assessment (8 patients), planned catheter-based interventions (6 patients), and arrhythmia ablation (3 patients). An intervention was undertaken either during or after 50 of the catheterizations (83%); 29 occurred at catheterization, 17 in the operating room (OR), and 4 both during catheterization and in the OR. Complications during catheterization were two myocardial perforations that were treated with pericardial drains (3%). Overall outcomes included successful decannulation of 39 patients, survival to hospital discharge of 26 (48%) patients, and longer-term survival of 23 (43%) patients (median follow-up, 35 months; range, 1 to 180 months). Fifteen patients were withdrawn from ECMO support due to severe neurologic impairment or lack of myocardial recovery.

CONCLUSIONS Cardiac catheterization can be performed safely on patients supported with ECMO. Catheterization during ECMO enables the diagnosis of residual lesions and can facilitate important therapeutic interventions. (J Am Coll Cardiol 2002;40:1681–6) © 2002 by the American College of Cardiology Foundation

Extracorporeal membrane oxygenation (ECMO) has been established as an important mechanical support for the failing circulation in children with heart disease (1–5). Accepted indications for ECMO in cardiac patients include low cardiac output, unexpected cardiac arrest, failure to wean from cardiopulmonary bypass (CPB), disproportional cyanosis, and refractory arrhythmias (5). Survival of cardiac patients on ECMO has improved since it was first reported in the early 1970s (6,7). From 1986 to January 2002, the cumulative international survival to discharge for cardiac patients supported with ECMO was 39% (8). Outcomes vary between institutions for a variety of reasons, but over the same time period at our institution, the cumulative survival to discharge for cardiac patients supported with ECMO was 54%.

Previous descriptions of catheterization during ECMO have been limited to single case reports (9–11) and small series of patients (12,13). Butler et al. (9) reported the use of ECMO to support a neonate with critical aortic stenosis during balloon valvotomy. Ward et al. (10) reported ECMO support during pulmonary artery stenting, and Ward et al. (11) described left heart decompression on ECMO with a long introducer across the atrial septum. Ettedgui et al. (12) described a series of nine patients undergoing catheterization while on ECMO where the primary procedure performed in six of these patients was balloon or blade atrial septostomy. Diagnostic catheterization was performed on the other three patients. The survival rate was 33%, including two patients transplanted within a week of catheterization. desJardins et al. (13) described 15 patients undergoing catheterization on ECMO. Interventions included four procedures at catheterization (three coil embolizations and one atrial septostomy) and four operations. The survival to discharge of these patients was 29%, and 14% (two patients) were alive at follow-up (43 and 73 months). These studies report patients from an earlier era of ECMO. As the use of ECMO to support the circulation after cardiac surgery has increased (8), so has the potential utility for diagnostic and therapeutic advantages of cardiac catheterization on ECMO. The purpose of this study is to describe our institution's experience with catheterization on ECMO, including indications for catheterization, subsequent interventions, and clinical outcomes.

METHODS

We retrospectively reviewed the medical records of all patients with known cardiac disease supported with ECMO at Children's Hospital Boston. Patients who underwent

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Abbreviations and Acronyms

CPB = cardiopulmonary bypass
ECMO = extracorporeal membrane oxygenation
ICU = intensive care unit
OR = operating room
SVT = supraventricular tachycardia

cardiac catheterization while supported by ECMO were selected for further review. Patient characteristics identified included age and weight at the time of catheterization and anatomical cardiac diagnoses. The patients' courses were documented including indications for ECMO and catheterization, any prior procedures, duration of time from ECMO cannulation to catheterization, and catheterization findings and subsequent interventions (catheter-based and/or operative). Patient outcomes were categorized as successful decannulation from ECMO (including cardiac transplantation), survival to hospital discharge and during follow-up, or withdrawal from ECMO support. Any complications from the catheterization or during the transport to and from the catheterization laboratory were recorded.

RESULTS

Between December 1984 and November 2001, 192 patients were supported with a total of 216 courses of ECMO for cardiac indications. Sixty catheterizations were performed on 54 of these patients (28%). Six patients underwent two catheterizations while supported with ECMO. The median age at catheterization was 22 days (range, 1 day to 36 years), and the median weight at catheterization was 4.3 kg (range, 1.9 to 81.5 kg). The anatomical diagnoses varied widely but included 24 patients with two-ventricle physiology who underwent 27 catheterizations, 14 patients with single-ventricle physiology who underwent 14 catheterizations, and 16 patients with varying types of cardiomyopathies who underwent 19 catheterizations (Table 1).

Table 1. Cardiac Diagnoses of Patients Catheterized on ECMO

Two-ventricle physiology	(n = 24)
Transposition of the great arteries	7
Tetralogy of Fallot	6
Ebstein's anomaly	3
Coarctation/pulmonary hypertension	3
Peripheral pulmonary stenosis	2
Other	3
Single-ventricle physiology	(n = 14)
Hypoplastic left heart variant	8
Hypoplastic right ventricle	4
Complex heterotaxy	2
Cardiomyopathy	(n = 16)
Acute myocarditis/endocarditis	6
Progressive dilated cardiomyopathy	5
Post-heart transplant	3
Restrictive cardiomyopathy	2

ECMO = extracorporeal membrane oxygenation.

Table 2. Indications for Cardiac Catheterization on ECMO

Indications	Number of Catheterizations (%)
Assessment of operative result	21 (35%)
Percutaneous left heart decompression	12 (20%)
Myocarditis/cardiomyopathy assessment	10 (17%)
Hemodynamic assessment (non-postoperative)	8 (13%)
Planned catheter-based interventions	6 (10%)
Arrhythmia mapping and ablation	3 (5%)

ECMO = extracorporeal membrane oxygenation.

Indications for ECMO. There were 56 courses of ECMO in the 54 patients. Two patients were supported with a second course of ECMO and underwent catheterization during both ECMO runs. Venoarterial ECMO was performed for 54 of 56 courses with either percutaneous cannulation from the neck or femoral vessels, or transthoracic cannulation of the right atrium and ascending aorta through an open sternum. Venovenous ECMO with cannulation via the internal jugular vein was initiated on two patients with both pulmonary and cardiac disease. The indications for ECMO included low cardiac output in 31 patients (55%), sudden cardiac arrest in 13 (23%), hypoxemia in 6 (11%), failure to wean from CPB in 4 (7%), and refractory arrhythmias in 2 patients (4%). The median time from ECMO cannulation to catheterization was 1 day (range, 0 to 11 days).

Indications for catheterization on ECMO. The indications for catheterization during the ECMO course are shown in Table 2. Patients with structural heart disease who acutely deteriorated, either during post-operative recovery or independent of surgery, were catheterized for a detailed hemodynamic assessment. Catheterizations to assess dilated cardiomyopathy or myocarditis were limited to pulmonary capillary wedge pressure measurement, coronary angiography, and possible endomyocardial biopsy. Planned catheter-based interventions were follow-up procedures on patients with lesions identified at prior catheterization during ECMO or just before ECMO, when interventions were initially deferred due to patient instability. Left heart decompressions were limited procedures to relieve left atrial hypertension in patients with left heart dysfunction. All catheterized patients had undergone prior transthoracic echocardiographic imaging, which was either suboptimal for diagnosis or suggested significant lesions amenable to therapeutic catheterization. Transesophageal echocardiography was infrequently used before catheterization on ECMO because of concerns regarding patient size, acuity, and risk of trauma to the upper gastrointestinal tract in anticoagulated patients.

Only one catheterization was performed in the intensive care unit (ICU). This adult-sized patient with Ebstein's anomaly was urgently placed on ECMO in the catheterization laboratory because of acute deterioration and cardiac arrest. Catheterization in the ICU using transesophageal echocardiographic guidance was performed to occlude an

atrial septal defect with a device. Two patients were placed on ECMO in the catheterization laboratory before the start of the catheterization. One patient had decompensated during transport to the catheterization laboratory and was stabilized with ECMO before the procedure. The second patient was electively transported to the catheterization laboratory for ECMO cannulation and left atrial vent placement with fluoroscopic guidance. All other patients were transported to the catheterization laboratory on ECMO. No patient was decannulated in the catheterization laboratory, and all were subsequently transferred back to the ICU or directly to the operating room (OR).

Post-operative catheterization on ECMO. Twenty-five patients (46%) underwent 27 catheterizations on ECMO (two patients were catheterized twice) within 10 days of a surgical procedure. The median time from surgery to cannulation in these patients was one day (range, 0 to 8 days), and the median time to catheterization after cannulation was three days (range, 0 to 11 days). The surgical procedures included tetralogy of Fallot repair (n = 5), stage 1 Norwood palliation (n = 5), arterial switch operation (n = 3), Senning/Rastelli operation (n = 3), heart transplant (n = 3), Fontan (n = 2), coarctation repair (n = 1), bidirectional Glenn shunt (n = 1), Senning operation (n = 1), truncus arteriosus repair (n = 1), and Blalock-Taussig shunt (n = 1). Twenty-one of these 25 post-operative patients (84%) underwent catheterization to assess the quality of the surgical repair; four of these patients had echocardiograhic findings of a residual lesion, nine patients were suspected of having residual lesions based on hemodynamic parameters measured in the ICU, and eight patients were catheterized for unexplained persistent myocardial dysfunction with failure to wean from ECMO after 72 h of support.

The three heart transplant patients had severe biventricular dysfunction immediately after transplant, and catheterization was pursued in these patients to assess hemodynamics and perform an endomyocardial biopsy for possible acute rejection. One post-operative patient with isolated left ventricular dysfunction and arrhythmias after a Senning/Rastelli operation went to catheterization for percutaneous placement of a left atrial vent to decompress the left heart. The same patient underwent a second catheterization on ECMO to place a pulmonary artery catheter to monitor pulmonary capillary wedge pressures during ECMO weaning. The other post-operative patient who was catheterized twice underwent diagnostic catheterization followed by an interventional procedure (coil closure of a ventricular septal defect) the following day.

Left heart decompression on ECMO. Twelve catheterizations were performed on 11 patients primarily for left heart decompression (left atrial vent or atrial septal stent placement). These procedures were performed in the setting of persistent left atrial and ventricular dilation as assessed by echocardiography, or persistent pulmonary edema on chest radiograph after initiation of venoarterial ECMO. Eight of these patients were supported with ECMO for cardiomyopathies with severe ventricular dysfunction. One patient with cardiomyopathy had been supported with two separate courses of ECMO and underwent left heart decompression during both courses. The remaining three patients who underwent left heart decompression included the post-operative patient with left ventricular dysfunction after a Senning/Rastelli procedure, a newborn with critical aortic stenosis with persistent left atrial and ventricular distention after balloon valvotomy, and a patient with acute thrombosis of a mitral valve.

Arrhythmia ablation on ECMO. Two newborn patients with severe Ebstein's anomaly and refractory arrhythmias underwent catheterization for radiofrequency catheter ablation on ECMO. The first patient had frequent episodes of supraventricular tachycardia (SVT) associated with severe hypotension that were resistant to multiple antiarrhythmic medications. She was placed on ECMO in the ICU to support her circulation during arrhythmia stimulation for intracardiac mapping and ablation in the catheterization laboratory. She underwent ablation of a Mahaim fiber and was successfully decannulated four days later. She remains free of tachycardia at follow-up. The second patient was diagnosed in utero with SVT. Post-natally, she was severely hypoxemic while in SVT and was emergently placed on ECMO. Her SVT was refractory to medical management, and she also underwent a transcatheter ablation procedure. The tachycardia was terminated initially with the first ablation but recurred several hours later. After a second ablation the following day, there was no recurrence of the SVT, and she was successfully decannulated. However, she died of multi-system organ failure and sepsis within a week of decannulation.

Repeat catheterization after ECMO resuscitation. Eight patients were placed on ECMO support after cardiac catheterization, three were urgently resuscitated with ECMO in the catheterization laboratory, and five were placed on ECMO in the ICU for acute clinical deterioration. Four of these patients returned to catheterization to complete planned interventions, and three patients underwent follow-up catheterization to reassess their hemodynamics. The remaining patient returned to catheterization for left heart decompression.

Subsequent interventions. Interventions were performed based on findings at 50 of the 60 catheterizations on ECMO (83%). Figure 1 shows the type of catheterization performed over time. Twenty-nine catheterizations involved interventions performed in the laboratory. Seventeen patients underwent operative interventions, and four patients underwent interventions both at catheterization and in the OR. Twelve of the 21 patients catheterized to assess the operative result underwent revision of the repair (57%), and eight patients underwent initial surgical intervention after catheterization on ECMO. Subsequent interventions are detailed in Table 3. After the 21 operative interventions, seven patients (33%) remained on ECMO or were transi-

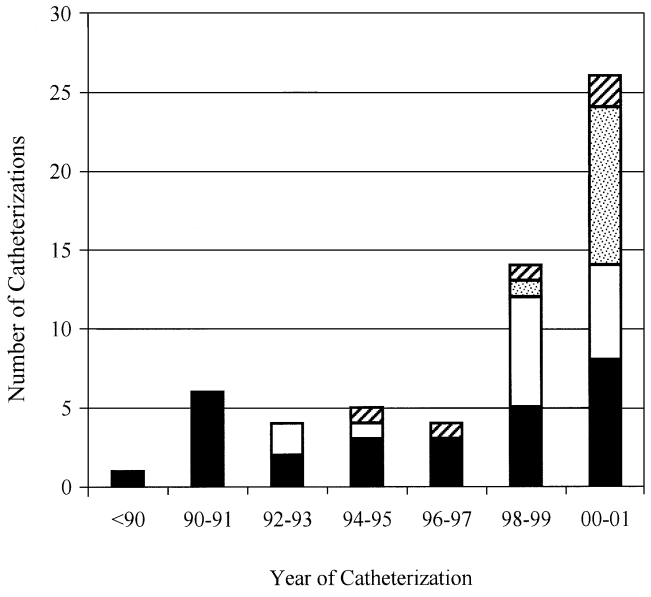

Figure 1. Type of cardiac catheterization performed on extracorporeal membrane oxygenation (ECMO) over time. "Interventional" refers to all other interventions performed at catheterization other than endomyocardial biopsy (EMB) and left atrium (LA) decompression. **Striped bars** = EMB; **dotted bars** = LA decompression; **open bars** = interventional; **solid bars** = diagnostic.

tioned back to ECMO support after CPB. One patient (5%) was withdrawn from support in the OR after failure to wean from CPB. The remaining 13 patients (62%) were successfully weaned from CPB or ECMO support before leaving the OR.

Complications. The complications observed during 60 catheterizations were limited to two myocardial perforations (3%). One perforation occurred through the left atrial appendage during a transseptal procedure to place a stent to decompress the left heart in a patient with critical aortic stenosis. The second perforation was presumed to be through the left ventricular free wall in a diagnostic catheterization in a patient with anomalous left coronary artery and a congenital diaphragmatic hernia. Both patients were newborns weighing less than 3.5 kg. Both patients were treated with pericardial drains without surgical intervention and survived the procedure. The patient with aortic stenosis was successfully decannulated and is alive at follow-up. There were no bleeding complications from the catheterizations. There were no transport-related complications of the ECMO circuit to or from the catheterization laboratory.

Outcomes. After catheterization, 39 of 54 patients (72%) were decannulated successfully (including six transplanted from ECMO), 26 (48%) patients survived to discharge, and 23 (43%) patients are alive at follow-up (median follow-up, 35 months; range, 1 to 180 months). Fifteen (28%) patients were withdrawn from ECMO due to severe neurological impairment or lack of myocardial recovery. Withdrawal from ECMO occurred a median of five days (range, 0 to 7 days) after catheterization. These patients were not considered to be transplant candidates either due to neurologic injury, multi-system organ dysfunction, or family preference. Figure 2 demonstrates the survival of patients catheterized on ECMO over time. The survival to discharge improved from 36% (4 of 11 patients surviving) during the early experience before 1994, to 44% (4 of 9 patients surviving) from 1994 to 1997, to 56% (19 of 34 patients surviving) during the most recent experience from 1998 to 2001. Our most recent experience of catheterization on ECMO (1998 to 2001) represents the majority of the catheterizations performed (65%).

Table 3. Subsequent Interventions Based on Catheterization Findings

Catheter-based Interventions	
Left heart decompression	
Percutaneous left atrial vent	9
Atrial septal stent	2
Amplatzer device removal	1
Balloon angioplasty	
Pulmonary arteries	4
Tricuspid valve	1
Vascular stent	
Pulmonary arteries	4
Restrictive bulboventricular foramen	1
Endomyocardial biopsy	5
Radiofrequency catheter ablation	3
Aortopulmonary collateral coil	2
Atrial septal defect device closure	1
Ventricular septal defect coil closure	1
Pulmonary artery catheter placement	1
Operative Interventions	
Revision of surgical repair	
Blalock-Taussig shunt revision	3
Thrombectomy (2 coronary, 1 right ventricle)	3
Pulmonary artery plasty	2
Tricuspid valvuloplasty	2
Conduit revision	1
Fontan takedown	1
Initial operative repair	
Arterial switch operation	2
Valve replacement	2
Stage 1 Norwood palliation	1
Coarctation repair	1
Atrial septal defect closure	1
Blalock-Taussig shunt	1
Surgical left atrial vent placement	1

DISCUSSION

The outcomes of patients in this series suggest that cardiac catheterization can be performed with minimal risk during ECMO and that catheterization often yields information that enables therapeutic interventions. The previously published series by Ettedgui et al. (12) and desJardins et al. (13) described the feasibility of cardiac catheterization of patients supported by ECMO. Approximately half of these catheterizations were diagnostic, with the majority of the catheter-based interventions performed being a balloon or blade atrial septostomy. In contrast with these earlier experiences, the majority of our catheterization procedures led to subsequent patient interventions, and our survival

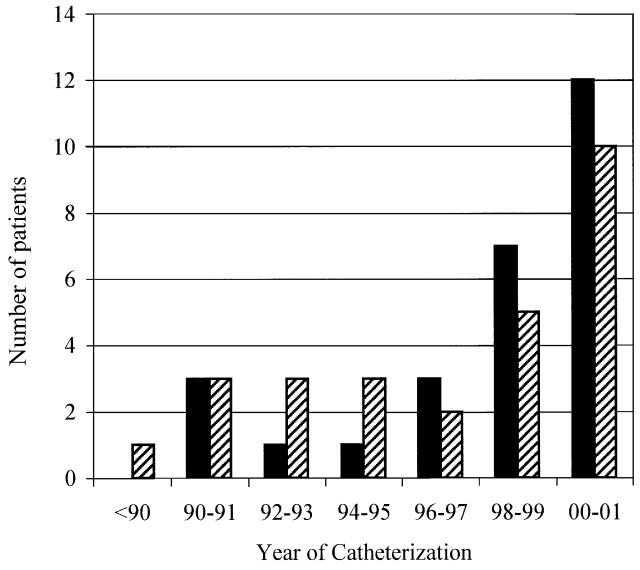

Figure 2. Survival of patients (n = 54) catheterized on extracorporeal membrane oxygenation over time. **Solid bars** = survivors; **striped bars** = non-survivors.

rates have steadily improved with our cumulative experience.

Diagnosis and subsequent interventions. In our series, findings at catheterization frequently resulted in subsequent patient interventions (83%). This was particularly notable in patients placed on ECMO in the immediate post-operative period, where 22 of 27 catheterizations (81%) led to subsequent interventions. We maintain a high index of suspicion of residual lesions in post-operative patients unable to be weaned from ECMO within 72 h of expected myocardial recovery (5). Transthoracic echocardiography is often limited in this setting, with less access to the standard views and altered ventricular ejection because of reduced preload while on ECMO. Catheterization during the ECMO course can facilitate the diagnosis of residual lesions that could limit successful weaning from ECMO. Early catheterization and subsequent interventions may also facilitate recovery of myocardial function and reduce ECMO duration, and thus the potential for ECMO-related complications.

Another important subset of patients undergoing interventions at catheterization included those requiring left heart decompression for severe ventricular dysfunction. This facilitates adequate venous drainage and ECMO flows, prevents over distension and injury of the systemic ventricle, and reduces left atrial hypertension and associated pulmonary edema. Balloon or blade atrial septostomy for left heart decompression has been previously described (14). Biplane fluoroscopy in the catheterization laboratory assists transseptal needle puncture required to decompress the left atrium and place a vent or stent. Five patients who underwent left heart decompression subsequently recovered ventricular function and were successfully weaned and decannulated from ECMO. In patients where the myocardium did not recover after decompression, three were transplanted from ECMO, and three were withdrawn from ECMO due to severe neurological injury.

Our series of patients also includes a novel use of ECMO to support two newborns with Ebstein's anomaly and SVT undergoing radiofrequency catheter ablation. Both infants had a very unstable circulation while in their tachycardia. The planned use of ECMO in these patients provided stable circulatory support during the required stimulation of SVT for intracardiac mapping and radiofrequency catheter ablation. Both infants tolerated the procedure well and were subsequently successfully decannulated.

Low risk of complications. Despite the logistical considerations for hospital transport of patients on ECMO, and the technical limitations of catheter-based interventions on fully heparinized patients, our incidence of complications was very low. The two complications we encountered involved perforations of the left atrial appendage and the left ventricular free wall, but both were well tolerated after a percutaneous pericardial drain was placed. Despite systemic heparinization, the perforations appeared to seal spontaneously before leaving the catheterization laboratory and did not bleed thereafter. There were no access-related complications in any of the patients despite full heparinization while on ECMO. Although we did not experience transport-related complications, the transport of these patients from the ICU to the catheterization laboratory is complex and labor-intensive involving nursing, ECMO specialists, and physicians. Experienced personnel and careful communication during patient transport facilitates the safe movement of patients between the ICU, catheterization laboratory, and OR without additional patient morbidity.

Improved survivals. Over our 17 years of experience supporting cardiac patients with ECMO, the survival of patients we have catheterized on ECMO has been improving. Our early survival to discharge was only 36% as compared with our more recent survival to discharge of 56%. This improvement likely reflects the difference in the time frame and increasing experience with cardiac patients on ECMO, the expansion of interventional catheterization techniques, and broader indications for ECMO. Extracorporeal membrane oxygenation has been increasingly used to support the circulation not only in patients after cardiac surgery, but also in patients with low cardiac output and cardiovascular collapse as a bridge to transplantation. Six of our patients with persistent myocardial dysfunction were successfully transplanted after catheterization.

Study limitations. While the survival of patients catheterized on ECMO has improved, our retrospective review cannot definitively prove that this improvement is due to the catheterization procedure. However, new information obtained from catheterization likely contributed to better outcomes. It would not be possible to determine prospectively if catheterization on ECMO changes patient outcome in a randomized, large-scale clinical study. Additionally, because our patients catheterized on ECMO were so diverse

in their anatomical diagnoses, indications for ECMO, and indications for catheterization on ECMO, it is impossible to identify accurate risk factors to predict future patient outcomes after catheterization on ECMO. The decision to pursue catheterization on ECMO is made on an individual case basis and is based on clinical judgment when the potential for new information gained at catheterization outweighs the risks of catheterization, and is believed to be crucial to optimize patient outcome.

Conclusions. Cardiac catheterization on ECMO is an important diagnostic tool for patients with a failing circulation requiring ECMO support. Catheterization can be performed safely with a low risk of complications and can facilitate important therapeutic interventions. Cardiac catheterization should be considered early in the ECMO course to facilitate correction of residual lesions as well as to support the failing myocardium with left heart decompression when indicated.

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